Summary Report (Phase I)
for

Littoral Geoacoustic Surveys Using an Adaptive Network of Gliders

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Overview

The goal of this multi-phased effort is to provide over-the-horizon characterization of the ocean water column and seafloor so that areas of safe operations can be identified and sonar performance can be accurately predicted. The tasks to accomplish this are: (1) use autonomous vehicles carrying wideband sensors to improve environmental measurement capabilities, (2) modify geoacoustic inversion algorithms to reduce solution ambiguity, (3) assess and characterize environmental geoacoustic variability and its impact on performance prediction algorithms, (4) develop techniques for extrapolating and interpolating geoacoustic inversion results, and (5) improve the utility of the environmental assessments for use in geographic information system (GIS)-enabled sonar performance prediction maps. Our program is designed to take advantage of, and contribute to, the technologies and operational concepts of the Persistent Littoral Undersea Surveillance (PLUS) program.

This report provides the phase I results and a preliminary phase II proposal for the geoacoustic inversion (GI) program of Alaska Native Technologies, LLC (ANT) and Applied Physics Laboratory - University of Washington (APL-UW). The system concept is briefly introduced and then the phase I results are presented. This is followed by an introduction to phase II. The planned activities for phase II are presented along with a schedule of the tasks to be completed. The report concludes with a look at the phase III work for this project.

The following were demonstrated during Phase I

- Adaptive ocean sampling functionality
- Necessary shallow water glider control to support proposed geoacoustic measurements was demonstrated at AUVFEST2005
- Modeling of system to show concept's credibility
- Evaluation of hydrophone data/recording integration
- Assessment of bistatic geoacoustic inversion requirements and effort required to modify APL-UW's Sonar Environmental Parameters Estimation System (SEPES) geoacoustic inversion tool for glider based data acquisition and geometries

These results provide reasonable technical basis for a Phase II that begins to implement a glider-based remote, over-the-horizon bottom characterization capability.

The primary areas of focus for Phase II are

- Show proof-of-concept for using gliders for battlespace profiling
- Incorporate bistatic, joint inversion (of forward and back scatter acoustic data) into SEPES
- Integrate wideband sensor array on ANT Slocum alongside UPS glider survivability work
- Integrate acoustic source on Seaglider which, combined with wideband processing, will provide additional gain against ambient noise. In conjunction with PLUSNet environmental support activities, a wideband source may also afford a target for the distributed sensor network
- Products to include a glider-mounted wideband source, a glider-mounted acoustic sensor array, and bistatic, joint inversion algorithms

1 Background

Acoustic sensor systems are the backbone of both anti-submarine (ASW) and mine-countermeasure (MCM) systems. In spite of this we continue to be handicapped by inadequate knowledge of the acoustic environment, especially in denied areas. Inadequate knowledge results from a lack of survey equipment, funding, and access to areas of tactical interest. Moreover, the acoustic environment can change substantially depending on conditions such as sound speed, water depth, and surface conditions. Predictability of specific acoustic conditions has proven to be a problem. Only the roughest estimates, by definition incorrect, are available for use by today's warfighter. The ability to measure the acoustic environment directly is essential. Of the many measurements possible the most useful to the warfighter are the sound velocity profile, bottom loss, and bottom reverberation.

Underwater gliders, that use buoyancy changes and wings for propulsion have recently (i.e., RIMPAC, TASWC, SHAREM) proved their ability to support U.S. Navy operations. They have operated for extended time periods (up to six months), in shallow (East China Sea) and deep (RIMPAC) waters, with high winds (typhoon) and in high currents (TASWEX). These underwater glider operations have primarily gathered temperature, salinity, depth, and current data. While this information is essential to the prediction of acoustic energy propagation, it only describes the propagation in the water column. However, acoustic systems in mid-to-shallow littoral waters are more affected by the composition of the bottom that dominates the energy loss and hence the propagation loss from a source to a receiver. Glider operations can help characterize the littorals.

As a result of mission successes, a technology transition initiative is underway to make gliders operational, distributed sensors for the warfighter. While gliders will prove themselves as useful sources of ocean structure data, without the capability to estimate bottom properties, they may not provide the complete information needed to support accurate sonar performance predictions and mission planning. A lack of accurate sensor performance predictions will lead to sub-optimal search, uncertainty in detection performance and potentially loss of ships.

Recent work by the SPAWAR PMW 180 meteorology and oceanography community through the Geoacoustic's Inversion Techniques (GAIT) evaluation shows much promise to the use of sophisticated algorithms that estimate the bottom composition from acoustic signals. There are two major issues with using acoustic inversion techniques. First, current operational sonar systems do not have the proper attributes for acoustic inversion. They lack calibration, dynamic range, and off-board acoustic sources. Second, it is very difficult to resolve ambiguities in estimating bottom properties (i.e., uncertainty in the sediment sound speed and attenuation) from the limited range of depths, ranges, and concomitant grazing angles at the bottom. Therefore, operational systems do not provide the requisite information to sufficiently characterize (for sonar performance prediction) the bottom composition.

Combining gliders with acoustic inversion techniques can provide a valuable measurement in a system that is robust and already undergoing technology transition. If successful, this SBIR can provide a hardware/software capability upgrade.

2 System concept

The system concept is shown in Figures 1a and 1b. Figure 1b shows the opportunity for measuring both loss and scattering from a bistatic glider geometry. Note that the acoustic propagation path can be even more complex, that is, incorporating multiple bounces in front of the receiver to provide multiple bottom loss measurement samples from a single ping. SEPES can invert measurements having several convolved bottom interactions (see Appendix A). A set of low-power long-range covert gliders may be used to invert bistatic acoustic measurements and obtain water column and bottom properties (compressional and shear sound speeds and attenuations, bottom layer thicknesses and roughnesses, and bottom densities) for purposes of GIS map construction and sonar system performance optimization. A potential countermeasure to gliders is to catch them in fishing trawler nets. To counter this, the phase II work proposes leveraging the threat avoidance work (see Figure 2) being done as a part of the UPS program. This includes using glider acoustic sensor arrays for better directionality (to null-out unwanted ambient noise) and a wideband acoustic source with broadband processing for improving signal to interference performance.

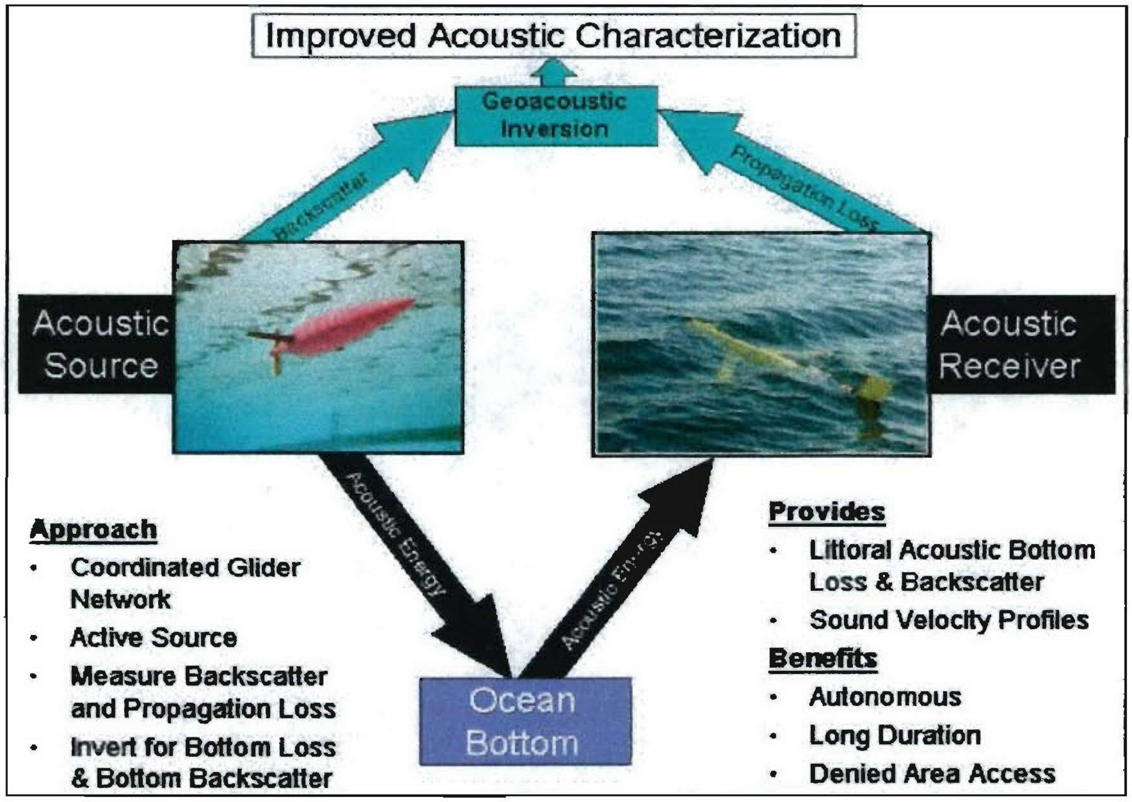


Figure 1a. System concept for the geoacoustic inversion process.

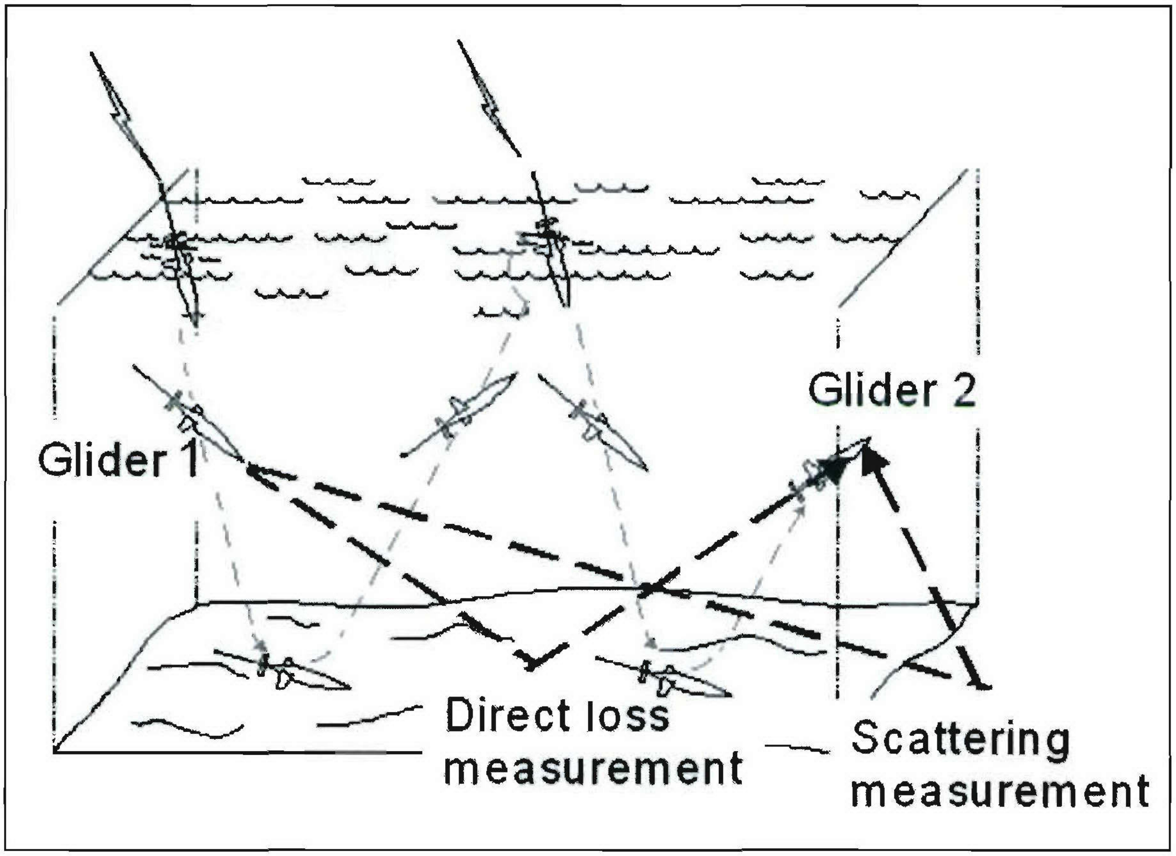


Figure 1b. System concept showing representative ray paths for the inversion process.

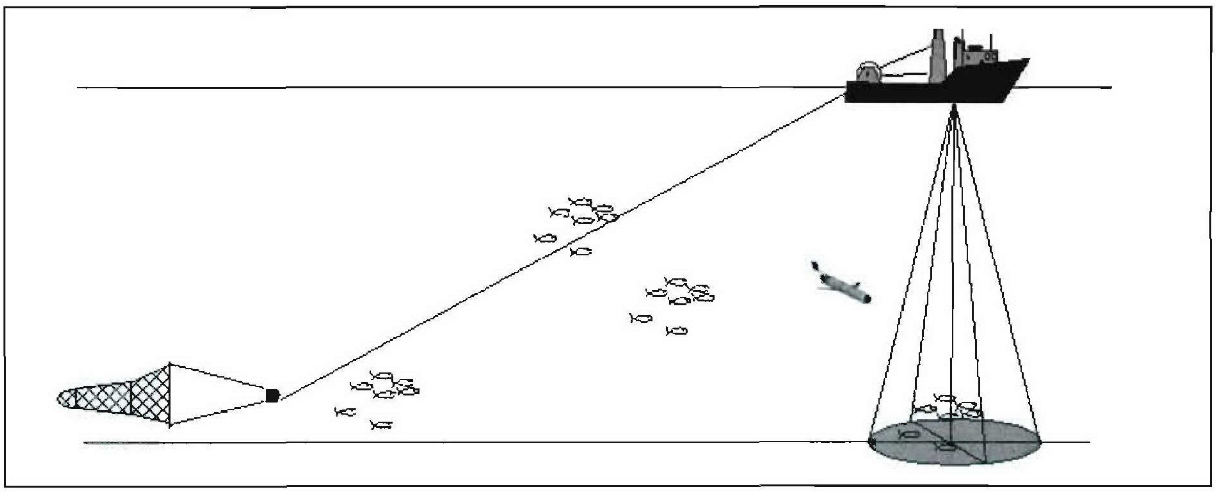


Figure 2. Fishing trawler avoidance concept for PLUS.

3 Phase I analysis and results

CASS (Comprehensive Acoustic System Simulation) was used to model a bistatic scenario involving two gliders in which the transmitting glider was trailing behind the receiving glider. The direct path CW signal from the source to the receiver is used to estimate the bistatic loss. Signals at longer times (e.g., bistatic reverberation) were determined and an analysis of combined eigenray arrival angle and energy versus time of arrival was conducted for source/receiver depth combinations of 25 m and 75 m in 100 m of water with 0.5 km and 1 km horizontal separation. The ITC-3013 acoustic transducer used aboard Seaglider as a pinger was assumed as the source (the ITC-3013 operates at 8 kHz with a 130 dB re 1uPa/V at 1 meter transmitter response with a nearly omni-directional beam - see Appendix B). At 8kHz the ITC 3013 just matches the ANT receiver high-end sensitivity limit (see Appendix C). This source level value was used as an exemplar of what could be available, but lower wideband frequencies are desired in Phase II. The ANT receiver was modeled as an omni-directional receiver.

The ambient noise was estimated from Wenz curves as 56dB at 8kHz and represents the signal cut-off for SEPES. An HFBL type-2 hard and fairly low-loss bottom was used in CASS along with a representative downward refracting sound speed profile (Figure 3a). With the sources in the mixed layer, the propagation loss is approximately 50 dB at 0.5 km, 60 dB at 1.5 km, and 65-70 dB at 5 km. Propagation loss is 80 dB at 5 km for sources close to the bottom. Figure 3b depicts reverberation level for a 25m/75m source/receiver combination along with the associated eigenray grazing angles (color). Compared with 56dB of ambient noise, it can be seen that the useful reverberation signal is short. Some directionality against ambient noise, afforded by limited array gain available to an autonomous underwater vehicle, together with wideband processing will provide a longer reverberation signal for inversion. Figure 3c depicts eigenray angle versus time (and energy amplitude assuming a 0dB source - in color). The two sets of eigenray plots represent multiple simultaneous eigenrays (either by their amplitude – received pressure level of each ray resulting from boundary and volume losses and bottom scattering strength - or angle of initial transmission) arriving at the receiver at each time increment. Some rays arrive via a shorter range higher angle path, others via a longer range flatter trajectory. These plots provided the indication that considerable grazing angle diversity is present in the signal although concurrent amplitude diversity reduces somewhat the practical utility of the diversity (e.g., higher angle rays are of lower amplitude). Bottom grazing angle diversity reduces bottom type estimation ambiguity.

This summary of our analysis demonstrates that gliders can be used as sources and receivers to estimate bottom composition, however the distance and depth requirements are fairly restrictive. Hence, it is important to consider whether or not gliders can maneuver with sufficient navigational accuracy to gather the data.

As a result, a phase I demonstration leveraging separate ONR funding was provided at AUVFEST2005 through a Rendezvous Event on June 15, 2005 in Dabob Bay, Washington. Figure 4 shows the simulated transmission loss (TL) and reverberation level (RL) geometries for the Seaglider and Slocum tracks. This AUVFEST2005 Rendezvous Event demonstrated close-aboard underwater glider operations over an extended period of time and helped mitigate some risk in the idea of controlling two gliders in close proximity. Two straightforward

geometries were selected by which TL and RL measurements will be made. Although RL/TL measurements were not actually taken during AUVFEST2005, the maneuvering geometries supported: (1) For TL, Seaglider pointed the Slocum from some range and closed with Slocum to get TL versus range. Slocum also pointed and closed with Seaglider or flew in station-keep mode. (2) For RL, Seaglider trailed Slocum with both vehicles aiming for the same distant waypoint, enabling TL and RL measurements from the same piece of seafloor for assimilation in SEPES.

The AUVFEST 2005 Rendezvous Event demonstrated glider station keeping to within 100 meters. This demonstrates glider maneuverability capabilities in line with the goals of PLUS. In all there were three gliders that participated in the three-hour Rendezvous Event: ANT's Slocum, a SPAWAR System Center Slocum, and an APL-UW Seaglider. Figure 5 shows an overall view for the three gliders of the Rendezvous Event. Figure 6 shows a close-up view of the event and Figure 7 presents the proximity results matrix showing on average better than 100-meter station keeping.

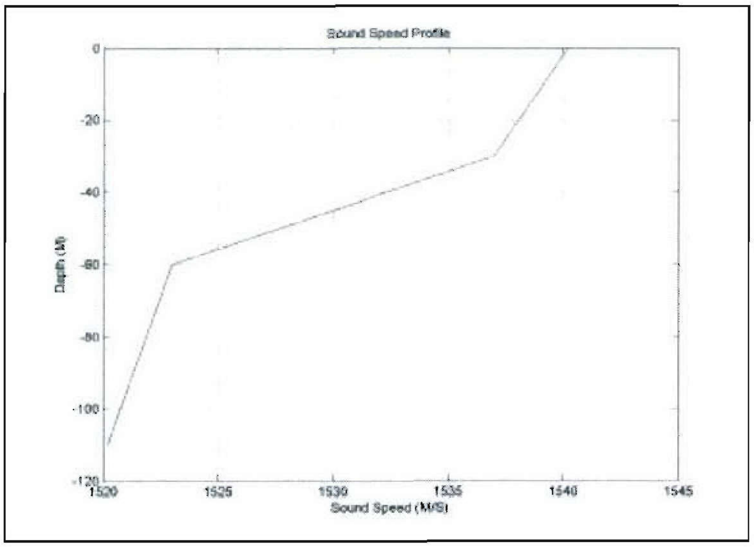


Figure 3a. Sound speed profile used in modeling.

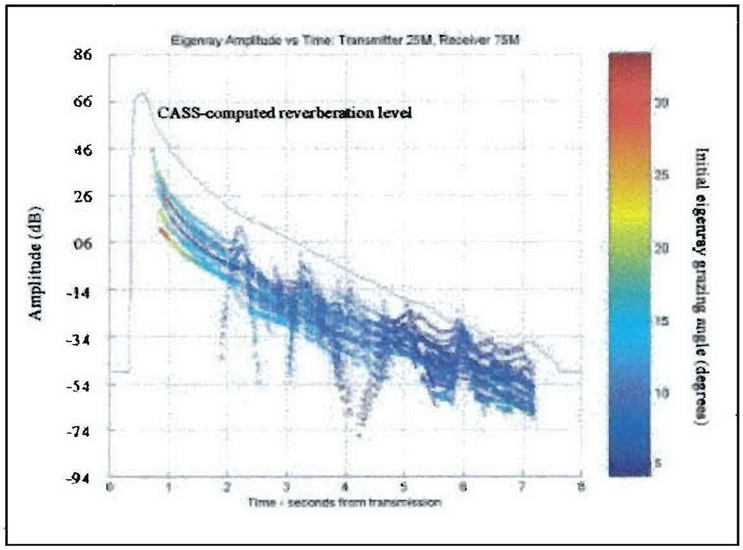


Figure 3b. RL computed from eigenrays—source 25 m, receiver 75 m.

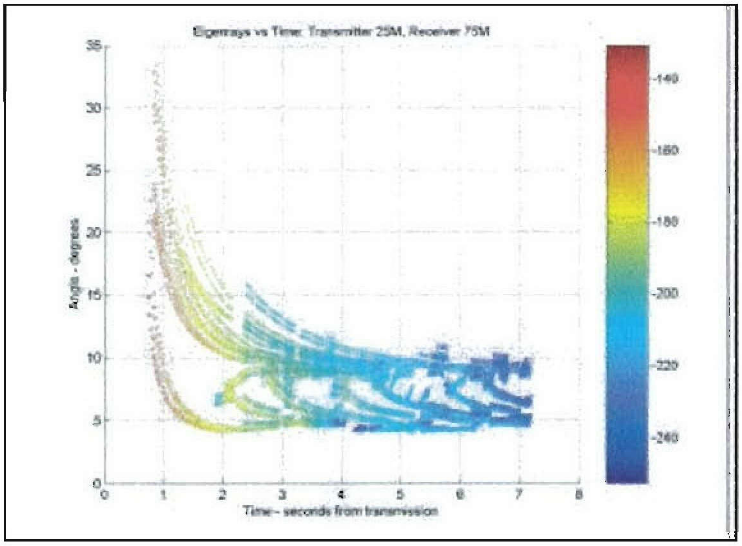


Figure 3c. Eigenray angle versus time (energy amplitude in color assuming a 0dB CW source level)—source 25 m, receiver 75 m.

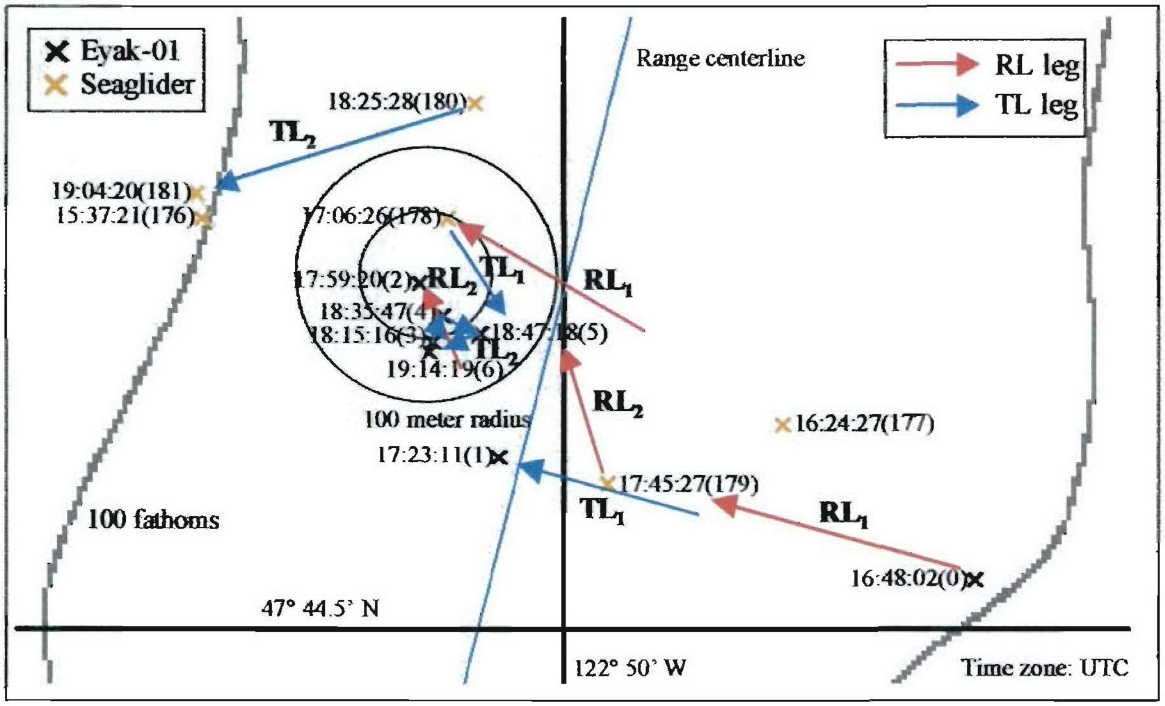


Figure 4. AUVFEST2005 Rendezvous event: TL/RL measurement scenarios.

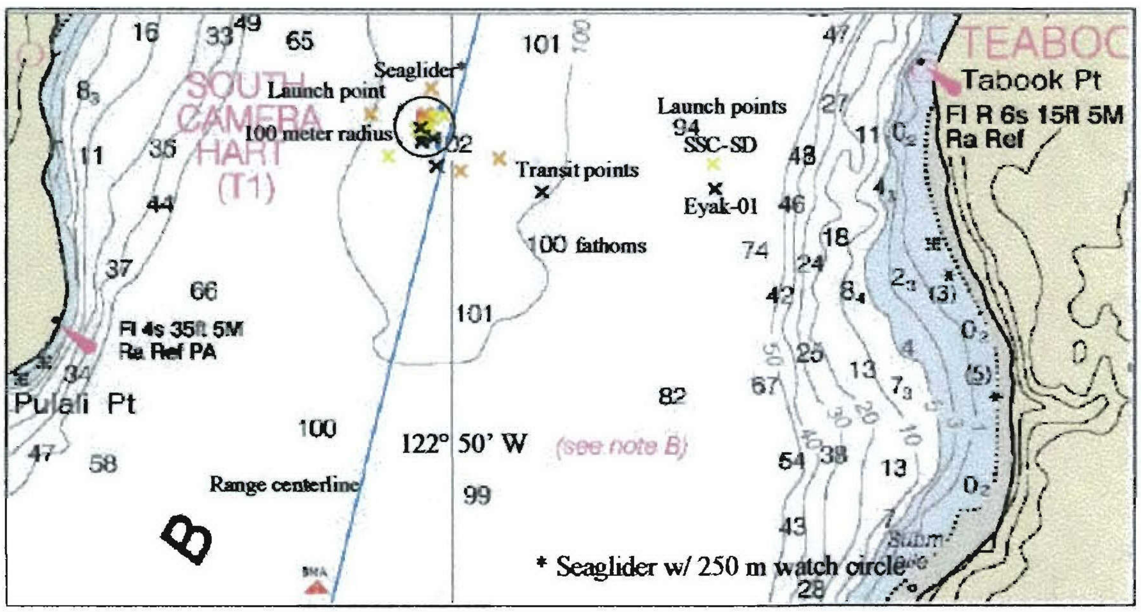


Figure 5. AUVFEST2005 Rendezvous event: full view.

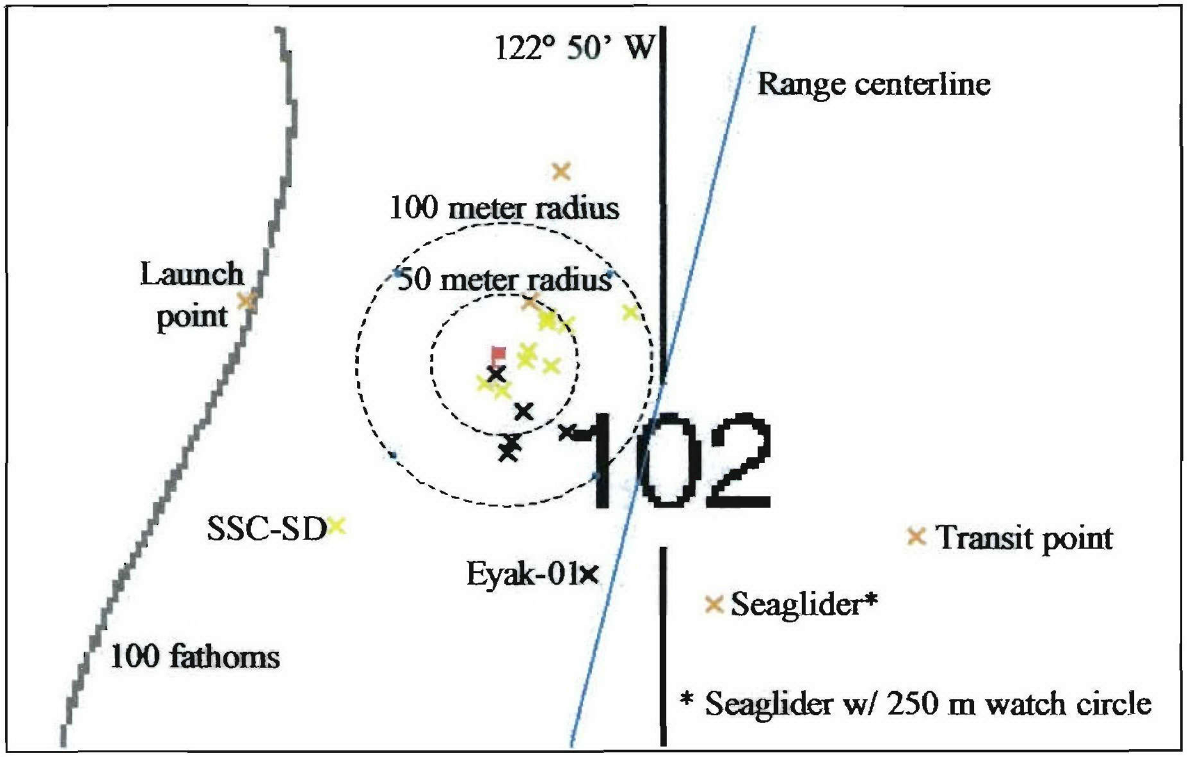


Figure 6. AUVFEST2005 Rendezvous event: close view.

Point of interest	lat (north)		lon (west)		Distance from rendezvous point (meters)	Median distance for respective glider (meters)
	deg	min	deg	min		
Rendezvous point	47	44.652	122	50.088	0	-
Eyak-01 P1	47	44.572	122	50.036	162	Eyak-01 58
Eyak-01 P2	47	44.650	122	50.087	4	
Eyak-01 P3	47	44.623	122	50.078	55	
Eyak-01 P4	47	44.635	122	50.072	37	
Eyak-01 P5	47	44.627	122	50.048	68	
Eyak-01 P6	47	44.619	122	50.081	62	
Seaglider P1	47	44.678	122	50.068	54	Seaglider* 150
Seaglider P2	47	44.560	122	49.966	228	
Seaglider P3	47	44.729	122	50.051	150	
SSC-SD P1	47	44.674	122	50.012	103	SSC-SD 45
SSC-SD P2	47	44.669	122	50.048	59	
SSC-SD P3	47	44.670	122	50.058	50	
SSC-SD P4	47	44.653	122	50.056	40	
SSC-SD P5	47	44.659	122	50.069	27	
SSC-SD P6	47	44.646	122	50.093	13	
SSC-SD P7	47	44.643	122	50.083	18	
SSC-SD P8	47	44.591	122	50.175	157	
SSC-SD P9	47	44.672	122	50.058	53	
SSC-SD P10	47	44.655	122	50.071	22	

* Seaglider w/ 250 m watch circle

Figure 7. AUVFEST2005 Rendezvous event: proximity results matrix.

4 Phase II overview

Goals

- Prove the utility of gliders for battlespace profiling, including data collection and environmental characterization for TDA's and GIS-based battlespace maps
- Evaluate wideband acoustic sources/signals for use on Seaglider to provide improved signal to noise and the frequency diversity for sufficient bottom characterization in support of operational acoustic sensor systems, and integrate the best source into Seaglider (PLUS bridge for APL-UW/Seaglider: environmental assessment)
- Implement wideband off-line signal processing for use in front of the inversion process
- Evaluate receiver characteristics including acoustic sensor arrays on an ANT Slocum and integrate the best sensor (PLUS bridge for ANT/Slocum: glider survivability)
- Incorporate bistatic, joint inversion processing into SEPES
- Provide a non-real time demonstration of the ability of gliders to gather sufficient data for inversion processing and show that processing the data provides a significant improvement in bottom characterization over current bottom databases

Products

- Glider-mounted wideband source
- Glider-mounted acoustic sensor array
- Wideband off-line signal processing to support inversion
- Bistatic, joint SEPES inversion algorithms
- Operations analysis for over-the-horizon glider-based battlespace characterization

5 Phase II plan

Our paired-glider design concept will allow covert autonomous over-the-horizon characterization of the ocean water column and seafloor.

In Phase II we will evaluate, integrate and demonstrate a wideband autonomous transmitter analogous to the Expendable or Submarine-launched Mobile Anti-submarine warfare Training Target (EMATT, SUBMATT) source – Lockheed-Martin-Sippican - for environmental characterization. The source will provide frequency agility for gain against noise and to help reduce bottom type estimation ambiguity. The glider pair provides geometric measurement diversity at the bottom to reduce estimation ambiguity. This glider-mounted wideband source will support PLUSNet in that it will be used for environmental characterization and potentially as an autonomous target source.

We will also demonstrate a glider-mounted acoustic sensor array. The acoustic sensor array will provide the beamwidth necessary to simplify the modeling problem to in-plane bistatic reverberation, and also reduce measured surface ambient noise. The wideband source will be a good acoustic match with the acoustic sensor.

Initial tethered vehicle demonstrations will serve as a control set for the inversion tests. The goal is to determine *ground truth* for a set of geoacoustic inversion bottom types of interest: (1) soft high-loss (unambiguous inversion), (2) hard low-loss (ambiguous inversion), and (3) complex range-dependent. For example, in the Pugent Sound region a potential area for demonstrations is Southern Dabob Bay from northwest of Misery Point towards the northeast past Hazel Point up towards Bangor. The waters around Misery Point offer a soft bottom with grey-green muds and clay (*R. W. Roberts*, 1974), while those around Hazel Point provide a hard bottom opportunity with nonzero shale and gravel concentrations, and large sand concentrations up towards Bangor. Nice regions of gradual and steep bathymetric changes (starting around 100 m) are also found just east of Misery Point on the fjord shelf.

Our phase I effort started late compared to the other Phase I contractors, yet we were able to reduce concept risk by demonstrating multi-vehicle control during AUVFEST2005, and confirm concept viability through bistatic modeling analysis for a pair of gliders. We will use SEPES, an ONR-developed algorithm, for inversion.

5.1 Bistatic, Joint SEPES

Implementing SEPES bistatic inversion modifications to CASS and SEPES has been designed during Phase I and will be implemented in phase II. The require changes to CASS and SEPES are outlined in the paragraphs below. Bistatic geometries used for design studies were a requirement not only for our proof-of-concept work, but also for understanding which models in CASS are exercised during these bistatic glider scenarios. Our phase I bistatic scenario modeling provides the basis for identifying the changes required to CASS and SEPES.

SEPES derives eigenray and environment information directly from CASS models. The CASS reverberation model does several things: (1) interprets transmitter and receiver eigenrays for range-dependent water column and bottom characterization; (2) applies filter equalization, source level, pulse length, beam widths, time delays, scattering area, and etc.; (3) integrates across frequency, bearing angles, etc.; and (4) computes reverberation. The SEPES strategy is to allow CASS to apply this complex combination of parameters, and transfer the essence of the CASS reverberation calculation into SEPES. For the monostatic case, reproducing the reverberation calculation with derivatives was fairly straightforward in SEPES. The newest CASS bistatic reverberation model (received in July 2005) contains some changes (compared with the monostatic case) that will be incorporated in this phase II effort.

The acoustic sensor arrays proposed for this effort afford us the advantage of narrow beams and directivity, which allows reducing the SEPES bistatic inversion to a single vertical plane passing through the source and receiver. This simplifies implementation and substantially reduces run times. (A narrow-beam receiver is required for this assumption to be valid for range-dependent environments.) The SEPES bistatic reverberation model will produce a 2-D matrix of grazing angle vs. time, which allows analytic calculation of the partial derivative of reverberation (at a time) vs. loss and scattering (at grazing angles). These derivatives can be chain-ruled with the analytic GABIM (Generalized Acoustic Bottom Interaction Model) partial derivatives to get the partial of the reverberation time series with respect to 2 layers of GABIM geoacoustic parameters. (An N-layer GABIM model with derivatives is nearly complete.) These sensitivities

are very important to an operations analysis for sea glider missions, in that geophysical inverse theory resolutions matrices (e.g., Figure 8), Fisher information matrices, and covariance methods for assessing environmental uncertainty are directly computable from the sensitivities. Hence, our approach offers substantial post-inversion analysis advantages over non-gradient based inversion methods (e.g., genetic algorithms, simulated annealing, particle swarm optimization, etc.)

Full benefit from variable glider measurement geometries will be realized when multiple measurements are fused in a joint inversion. The input to the joint inversion will be *several* bistatic reverberation time series collected by the gliders. The model (CASS) will require a different geometry setup (e.g., different source/receiver depths and locations) for each measurement. SEPES will be augmented to run these several reverberation calculations in parallel to affect a joint inversion. This clearly would benefit from coarse-grained parallel computation to reduce time to solution.

Full joint, bistatic inversion is not required to assess how valuable the additional information afforded by the frequency and geometry diversity of the gliders can be. Sensitivities (derivatives) produced by single model runs for a particular geometry can be combined with sensitivities from other geometries to form a joint derivative matrix (without actually doing a measurement). Model and data resolution matrices computed for the joint matrix quantify the additional information derived by adding a hypothetical new measurement geometry to the mix. The resolution matrices will explicitly show which additional loss or scattering angles and/or which additional GABIM parameters can be resolved by adding new measurement(s). For example, Figure 8 shows the model resolution matrix computed by SEPES for a monostatic reverberation measurement inversion. The figure shows good resolution of the second layer, but confusion among some parameters in the first layer. The goal is to find measurement geometries providing joint inversion data to reduce this confusion. This forms the analytic basis for future work in glider measurement scheduling. Just to be clear, a joint inversion capability does not need to be implemented in order to perform this analysis. It can be done using sensitivities from several single runs of a model that produces sensitivity matrices. The joint inversion will be required when several bistatic measurements are available for estimating unknown sea bottom characteristics.

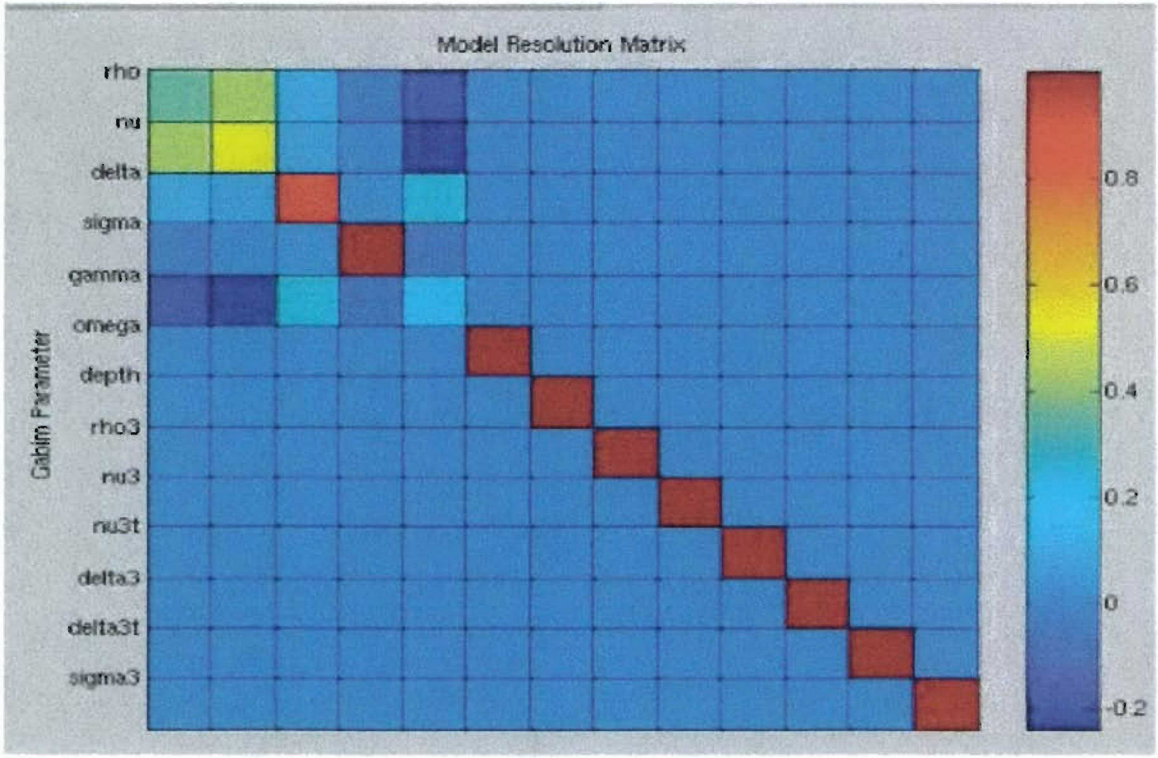


Figure 8. SEPES-derived model resolution matrix for 2-layer GABIM geoacoustic parameters from a monostatic reverberation inversion.

5.2 Wideband acoustic signal processing

Wideband acoustic signal processing offers three principal advantages (over a harmonic source): finer resolution, improved SNR via time-bandwidth processing, and acoustic signature capability (capturing the scattering and loss as a function of frequency). For classification purposes it is the last that gives wideband processing the ability to distinguish similar targets, increase detections and decrease false alarms (*Simpson, Denny, et al.*, 1993-2003).

The attributes of wideband techniques have been known for about 40 years (*Rihaczek*, 1969), but the implementation into the sonar world has been a function of the advances in technology to attain the requisite bandwidths and processing power to do the computations. Physical implementations have been realized in the radar world for many years to achieve these same results. Sonar systems, because of the relative slowness of the speed of propagation, force other physical realizations that have higher computational demands than the radar case.

In the technique, resolution is the pulse width compressed by the signal's time-bandwidth (TBW or TB in some papers) product (*Rihaczek*, 1969). This enables a 2m pulse to be compressed, realistically, to 1.5 cm – a potential that cannot be duplicated in the classic sonar case. Another facet of this compression, given the design of the receiver, is an improvement in SNR

proportional to the TBW product. A system with 50 kHz bandwidth and a 1.5 msec pulse then has a TBW = 75 (a unitless number) and an improvement of 10Log(TBW) or 18.75 dB. Experiments have been conducted on the reality of the gain and have shown that nearly all of the predicted gain is realized if the medium remains stable and relatively non-dispersive, and frequency dependent absorption is accounted for. Pulse compression is achieved by designing the receiver to look for the unique transmit pulse, often called Matched Filtering.

An additional feature ANT exploits is the attainment of signatures from targets in the water column. ANT personnel have been successful in classifying fish species with >85% confidence by using signature data alone. Fundamentally, different frequencies develop a different reflectivity off of objects, either the surface or internal structure, that yields different total reflected spectra. This is similar to the optical case of visual recognition of plants or panels of different woods by an observer because of the differences in color reflected back.

The penalty for wideband acoustics is a heavier processing load, higher digitization rates and more data overall to handle and store. The Matched Filter can be implemented in either the time or frequency domain, however there is a computational savings by performing the convolution in the frequency domain. This forces either large DFT's or the necessity of doing overlap-add functions on successive smaller DFTs. In order to acquire data of sufficient quality, the minimum digitization rate must be at-least the Nyquist frequency of the highest frequency in the band of interest, e.g. the 50-90 kHz signal would require approximately a 200 KS/s A/D per channel data rate, vice an envelope detected signal that could be A/D'd at perhaps 1 KS/s. In this example, approximately 200 times as much data must be taken and handled. This again forces data storage/transmission unless the results are not kept on site but either transmitted or reduced. If reduction is desired, additional processing is needed, plus validation of the process.

6 Phase II schedule

The proposed phase II schedule lasts two calendar years and is shown in Figure 9. The schedule starts with three interdependent tasks (1) constructing an autonomous bistatic range-dependent geoacoustic inversion program, (2) implementing a receiver array in parallel with PLUS vehicle survivability work, and (3) incorporating a wideband acoustic source in parallel with PLUS environmental assessment work.

The next step (beginning with Task 4) is tethered vehicle inversion demonstrations (possibly using a non-integrated source versus tethered receiver if task (3) cost/schedule considerations warrant) both in simple and complex *ground-truth* environments with unambiguous and ambiguous bottom types. Ambiguous bottom types for purposes of geoacoustic inversion are hard low-loss bottoms (a type-2 bottom province is hard and fairly low-loss). The base part of the schedule concludes with a report and briefing. The options include dynamic vehicle demonstrations in range-dependent environments with an accompanying report and briefing.

In all, the schedule is as follows with timeline as shown in Figure 9.

Phase II proposed tasks

Base:

Task 1 – Geoacoustic bistatic inversion method construction
- Task 1.1 – Bistatic, joint SEPES development
  - *Deliverable*: Bistatic, joint SEPES inversion algorithms
- Task 1.2 – Range-dependent geoacoustic inversion analysis
  - *Deliverable*: Operations analysis for over-the-horizon glider-based battlespace characterization

Task 2 – Acoustic receiver array
- Task 2.1 – Glider integration
- Task 2.2 – Beam pattern and beamforming analysis
- Task 2.3 – Sampling strategy
  - *Deliverable*: Glider-mounted acoustic sensor array

Task 3 – Wideband acoustic source
- Task 3.1 – Identify and integrate wideband source
  - *Deliverable*: Glider-mounted wideband source
- Task 3.2 – Develop wideband signal-processing algorithms
  - *Deliverable*: Wideband off-line signal processing to support inversion

Task 4 – Tethered vehicle inversion demonstrations and analysis
- Task 4.1 – Simple ground-truth environment: unambiguous bottom type
- Task 4.2 – Simple ground-truth environment: ambiguous bottom type
- Task 4.3 – Complex environment inversion test

Task 5 – Analysis report (base)
- Task 5.1 – First briefing

Option:

Task 6 – Dynamic (flying) vehicle demonstrations and analysis
- Task 6.1 – Simple range-dependent environment: unambiguous inversion test
- Task 6.2 – Simple range-dependent environment: ambiguous inversion test
- Task 6.3 – Complex range-dependent environment inversion test

Task 7 – Analysis report (option)
- Task 7.1 – Second briefing

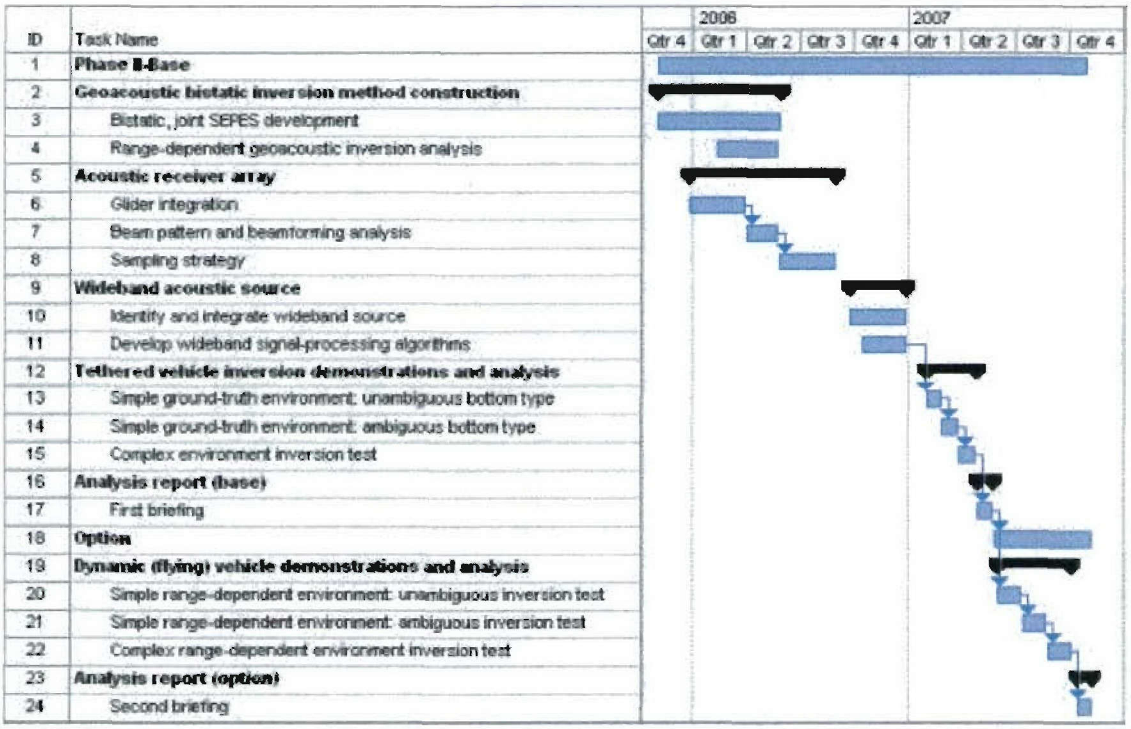


Figure 9. Phase II schedule.

7 Phase III

Our vision is a network of autonomous agents working to reduce the risk of underwater attack to the fleet. This program is designed to integrate the glider, sensor, communication, modeling, inversion, and environmental characterization capabilities required to realize this vision.

We are developing the gliders, sensors, and processing required for making the necessary measurements to adequately characterize the littoral undersea environment. We are expanding geoacoustic inversion to reduce estimation ambiguity (or characterize it when it cannot be reduced), assess and resolve local geoacoustic inversion variability, and extrapolate and interpolate environmental characterization results. Employing more than one source-glider will provide the added capability of more accurately locating the receiver glider's position in azimuth as well as range to improve measurement localization. Our approach directly supports geoacoustic databases (e.g., GDBV), battlespace characterization, and sensor performance prediction tools including GIS-enabled sonar performance prediction maps.

Acoustic and satellite-based communications will be required to affect cooperation among a network of gliders, and for transmitting data ashore. High bandwidth underwater communications requires vehicles operating in close proximity over an extended period of time. Phase I of this project demonstrated this capability through the Rendezvous Event at AUVFEST2005. Future work will include a tradeoff analysis of techniques (high/low rate acoustic communications, network design, onboard vs. off-board processing, and advanced signal compression) for improving optimal glider network performance.

Appendix A

Inversion Ambiguity Reduction Using Data Fusion

The Applied Physics Laboratory at the University of Washington (APL-UW) has pioneered the estimation of ocean environmental parameters from combatant sonar reverberation measurements using inversion techniques developed in the Sonar Environmental Parameter Estimation System (*Anderson et al.*, SEPES 2002) the OMAL-certified Geo-Acoustic Bottom Interaction Model (GABIM) (*Odom and Moravan*, 2001) extended to compute analytic derivatives.

SEPES estimates bottom and surface loss (BL/SL) scattering strength (BSS/SSS) or GABIM geoacoustic parameters from measured sonar reverberation.

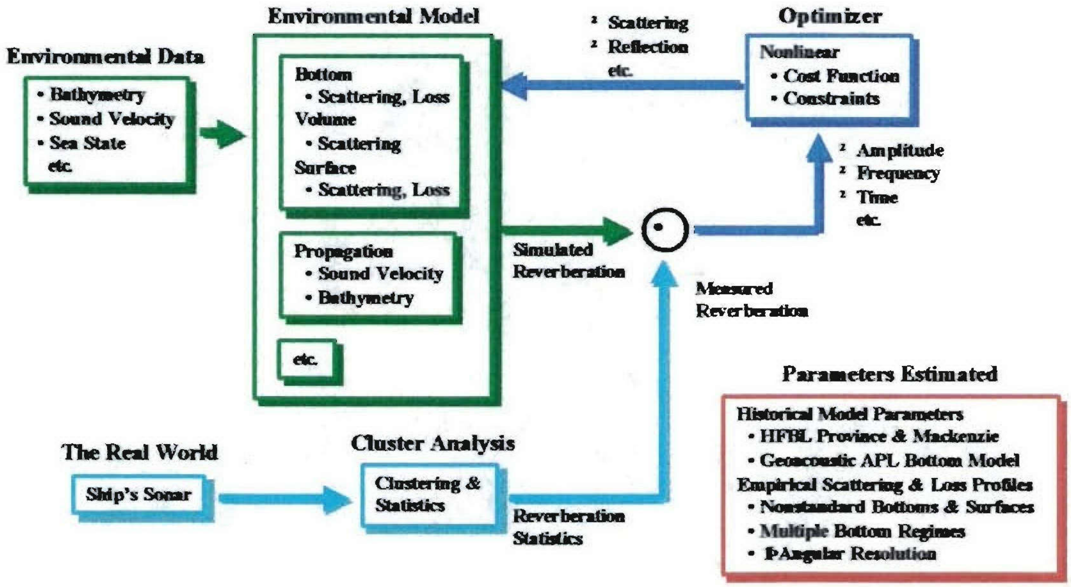


Figure A-1. ***SEPES processing scheme.***

SEPES estimates the parameters shown at the lower right in Figure A-1. An ocean environmental acoustic model (typically CASS) is initialized with environmental data that can be measured *in situ*. The model computes reverberation and partial derivatives of reverberation with respect to the environmental parameters being estimated (e.g., bottom loss, surface scattering). Reverberation measurements collected by a sonar system are fed into a clustering algorithm to group similar data examples for averaging prior to estimation. The mean value of each cluster is computed and compared to the output of the acoustic model. A nonlinear constrained optimizer is used to automatically adjust the model inputs (e.g., bottom loss, surface scattering) to match the model to measured reverberation.

SEPES processing is organized into the four segments of clustering, windowing, initialization, and estimation, as described below.

SEPES is effective for estimating bottom characteristics relevant to in situ sonar performance prediction for a variety of reverberation sources, including hull-mounted, towed array, torpedo, and buoy-based sonar's. These in situ techniques are effective under restricted acoustic conditions, that is, processing a single sonar ping or a small set of morphologically similar pings measured under consistent sound speed, water depth and measurement geometries. But they fall short of filling the Navy need for creating accurate bottom province databanks from combatant measurements. Two major problems remain: observability of the bottom and combining data from multiple measurements (data fusion).

Limited Observability

A significant challenge to determining the bottom *type* (geoacoustic properties) from combatant reverberation measurements is the small range of grazing angles typically observed in a ping of reverberation data. Figure A-2 shows a representative situation to all types of sonar systems. This particular situation is model output the air anti-submarine warfare (ASW) Harsh Environment Program (HEP) flights in the Gulf of Oman (*Karalus*, 1993). The figure shows eigenray traces for a set of padded sonobuoys at two different depths, and the fact that acoustic conditions typically allow only a limited set of eigenrays to propagate to longer ranges, thereby limiting the grazing angles information collected from the bottom. The figure also shows that sources placed at different depths support different grazing angles.

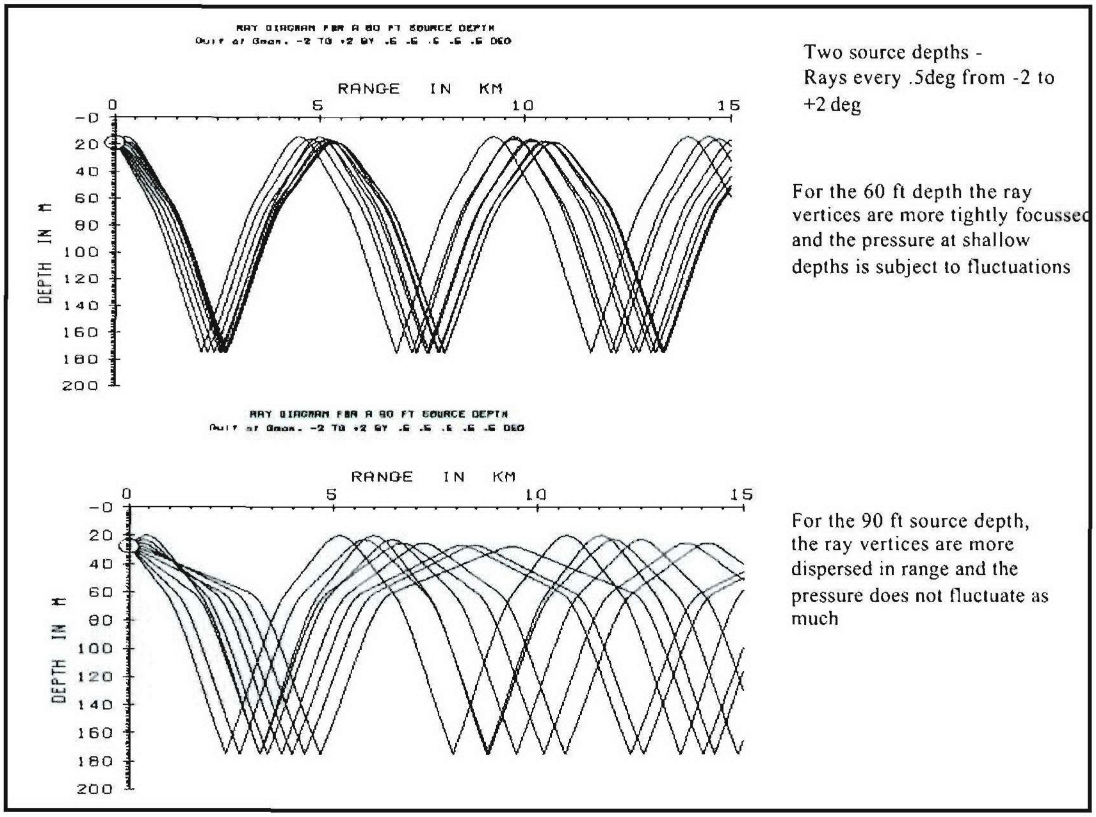


Figure A-2. Eigenray traces for 60- and 90-ft source depths.

Figure A-3 shows the partial derivatives of reverberation with respect to bottom loss for the reverberation computed from the eigenrays in Figure A-2. The derivatives indicate that the range of bottom loss grazing angles contributing to the observed reverberation is fairly limited – ranging from about 4° - 25° at short range (up to 5 seconds) decreasing to about 4° - 8° at maximum range. Two views (with viewpoints that differ by 180°) of the derivative surface are shown. These derivatives give insight into the sensitivity of reverberation to changes in bottom loss and scattering.

Although this example is from a high source level surface ship sonar, the discussion applies to bistatic glider operations. Bottom grazing angle diversity helps reduce estimation ambiguity, regardless whether the diversity comes from a long reverberation sequence from a surface ship sonar, or from bistatic measurements taken by gliders and fused together in an joint inversion.

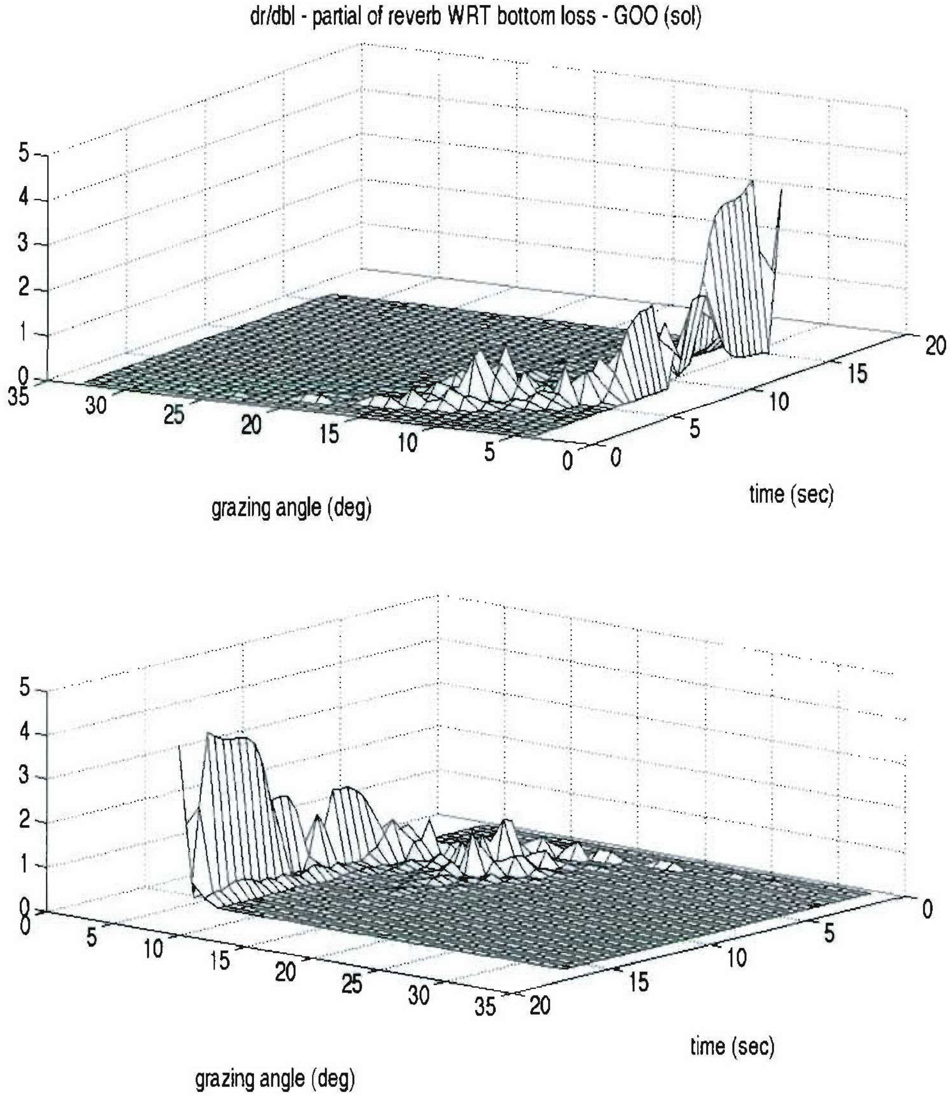


Figure A-3 – Partial derivatives of reverberation w/r to bottom loss.

It is clear that the reverberation level at short range depends on higher angles, but is not very sensitive to bottom loss. As the time increases, the angles contributing to reverberation decrease, but the sensitivity increases. A value of three on the vertical scale here implies that a 1-dB change in reflection loss causes a 3-dB change in reverberation level. The down-bending profile, combined with the chosen source depth, gives a minimum bottom angle of about 4° for this situation.

This limited range of observable grazing angles causes significant problems because bottom loss and scattering for the various bottom types can be very similar for any particular range of grazing angles. Figure A-4 shows bottom loss curves computed by the GABIM for one frequency represented in the data of Figures A-2 and A-3.

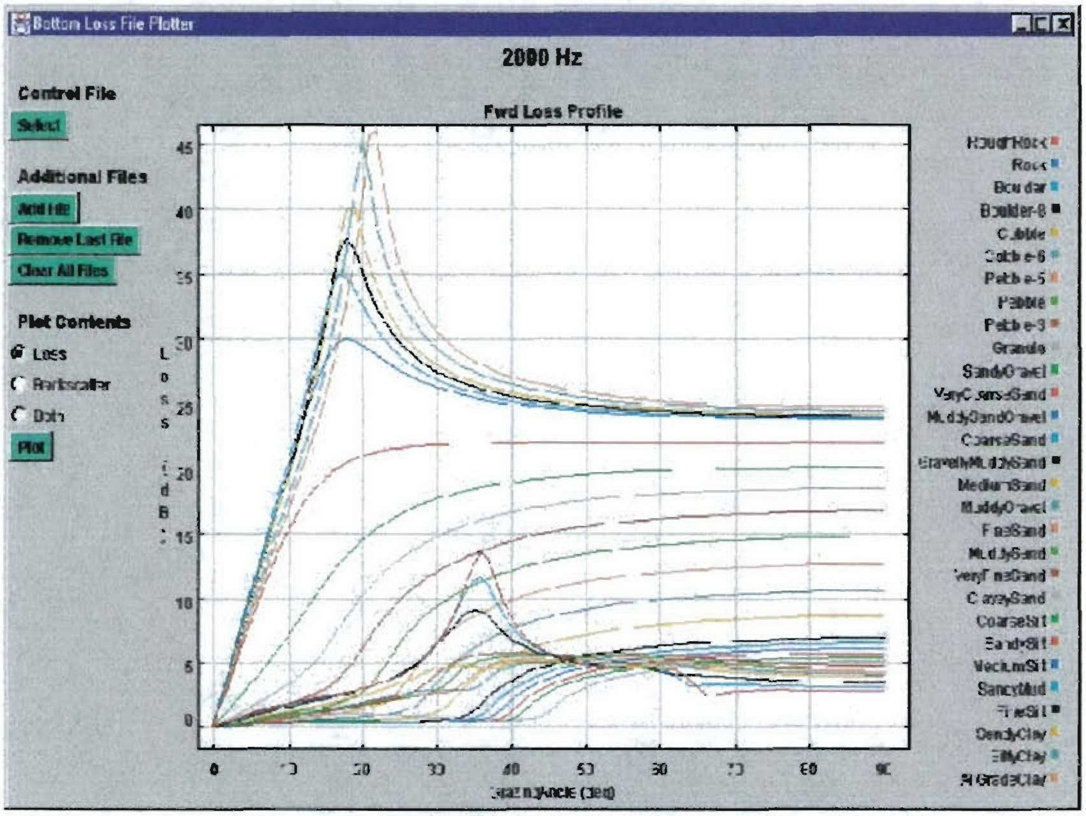


Figure A-4 – GABIM-generated bottom loss for 29 bottoms a 2000 Hz.

It is clear that the bottom loss characteristics are fairly ambiguous for grazing angles of 4° to 8° for groups of softer and harder bottoms. Things don't get much better even considering loss information out to 20°. APL-UW addresses this problem in two ways: (1) nonlinear constrained optimization techniques are used to invert empirical loss and scattering curves sensitive only to grazing angles contributing to the observed reverberation; and (2) Analysis of Variance (ANOVA) is used to rank-order bottom type estimates into groups of similar and dissimilar types.

Data Fusion

The promise for using bistatic gliders for future ocean parameter estimation is to substantially increase the amount of information available for processing by fusing measurements taken from a mixture of measurement conditions. Combining measurements from multiple geometries is exactly what is required to solve the limited observability problem. Figure A-4 shows that measurements at 20° and 30° offer substantial opportunities to discriminate within the soft and hard bottoms types, respectively. Other frequencies offer opportunities in other angle regimes.

Consider reverberation measurements of a single patch of bottom having a slope. Simply repositioning the ship to take measurements looking up, down, and cross-slope provides up to twice the grazing angle diversity, which may be sufficient to disambiguate the bottom type. Such opportunities exist today along ship-measured reverberation tracks, simply by organizing the measurements into a databank that geometrically relates multiple measurements of the same patch of bottom.

Current ocean parameter estimation techniques can leverage the techniques outlined here in a sensible, statistically sound manner. For instance, the ANOVA mentioned earlier helps disambiguate bottom type by taking advantage of diversity in sonar measurements, and the physics-based relationships imposed by the GABIM model. The ANOVA can be employed whenever there are sufficient degrees of freedom (e.g., multiple samples of the same bottom via a wideband measurement providing two or more frequencies, or multiple measured depression/elevation angles.) The ANOVA identifies the fittest bottom type, and a set similar bottoms whose difference from the fittest is statistically too close to call.

Grouping multiple measurements from a single bottom type together for analysis is also a challenge. SEPES uses morphological clustering techniques to sort measurements into groups for analysis. An example is shown in Figure A-5. Although the morphological technique is effective, one major disadvantage is that multiple measurements from a common population (e.g., a particular bottom type) taken with the measurement diversity we seek to leverage here are unlikely to be grouped in the same cluster. This characteristic is often observed in the SEPES clustering results, where up, down, and cross-slope reverberation measurements typically fall into different clusters. More robust, model-based techniques such as expectation maximization could be used assemble diverse observations of a population (e.g. a particular bottom type with some geographic extent) for fusion, and to throw out observations that are clearly statistical outliers and not measurements of the population. The constrained optimization techniques mentioned above can also leverage measurement diversity model-based relationships in a direct fashion.

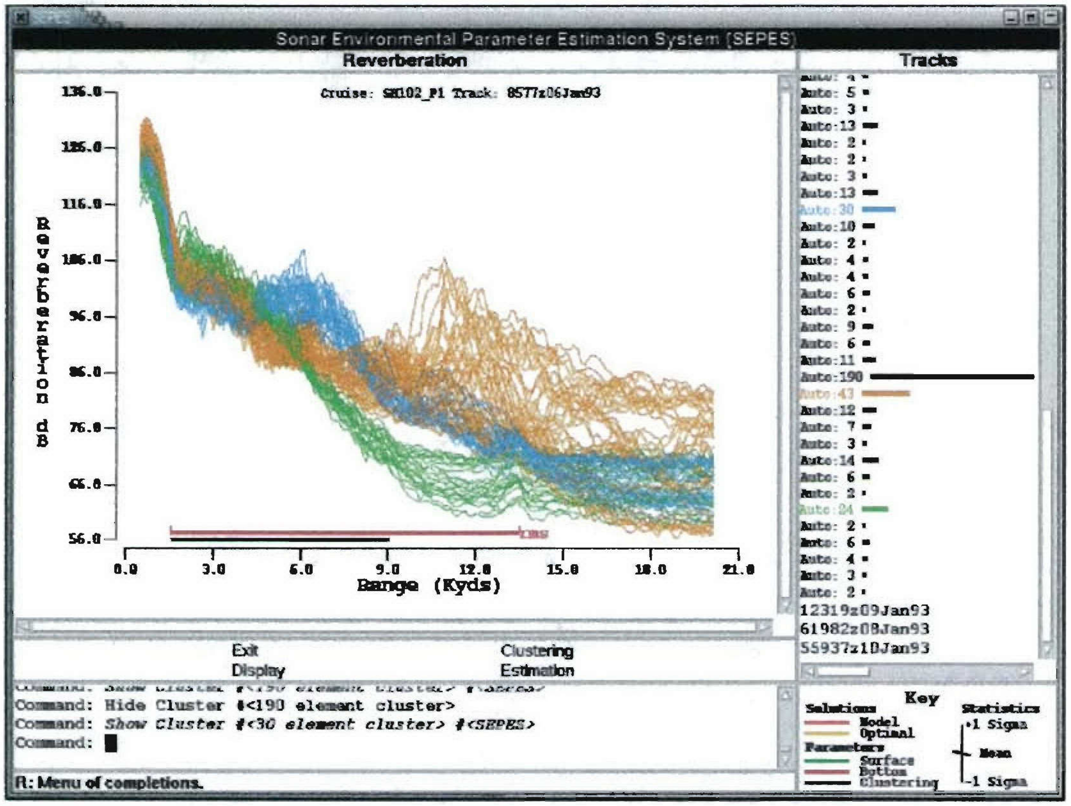


Figure A-5. Three SEPES clusters computed from 360 reverberation traces. The original data exhibits approximately 30 dB of amplitude variability.

Objective

Our objective is to build a data fusion methodology that automatically assimilates related measurements together in clusters (geographically co-located or not), combines those measurements in a joint estimation of significant ocean environmental parameters using underlying physics-based ocean acoustic models. Since many of these parameters are time varying, our focus will be on databanking bottom geoacoustic parameter estimates.

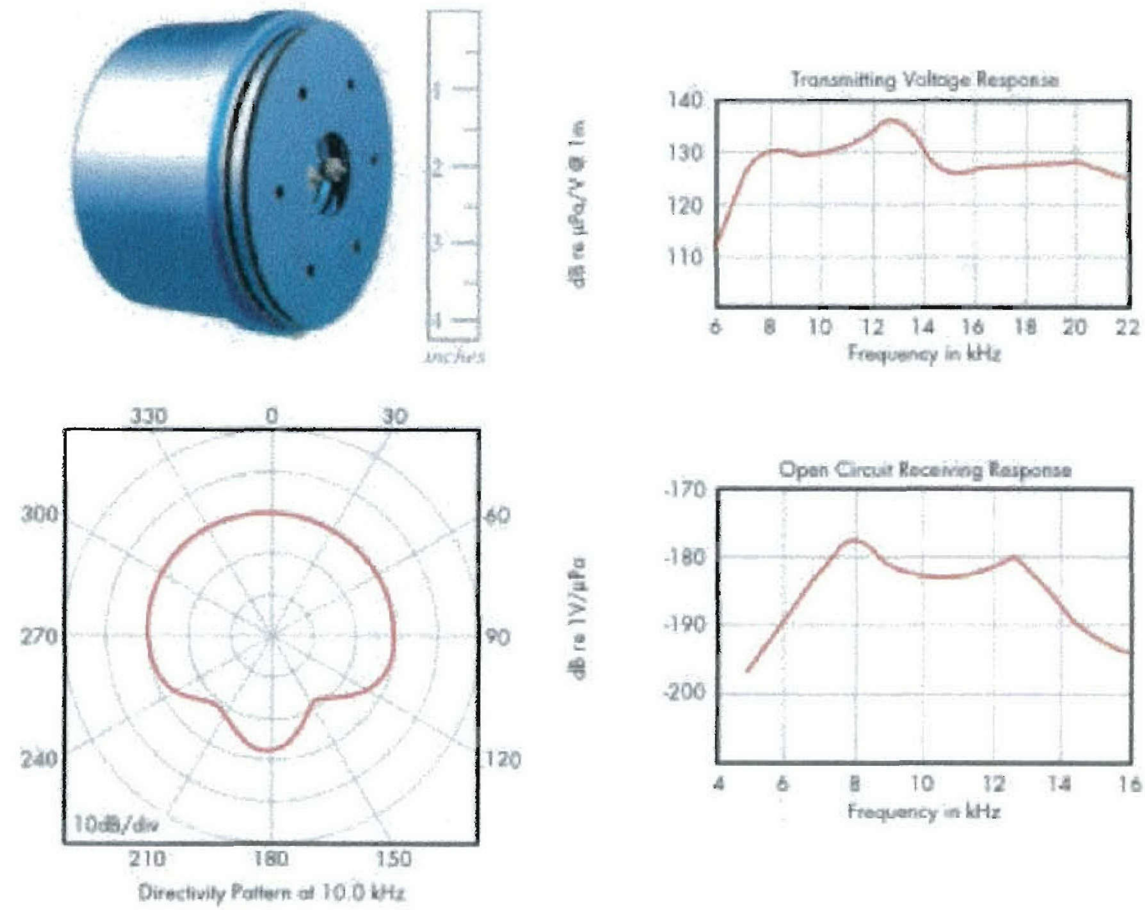
Technical Approach

Our approach is to: (1) assimilate sufficient glider-based measurements to make the solution to an optimal parameter estimation problem unique (e.g., make the bottom parameters observable); or (2) if sufficient information is unavailable, make non-unique estimates and identify the uncertainty in the result. The models used for parameter estimation are CASS and GABIM. GABIM is a contemporary bottom loss and backscatter model developed by APL-UW for the U.S. Navy, and is currently in the OMAL review process. GABIM calculates bottom loss and scattering for multi-layered bottoms at all sonar frequencies, but is difficult to invert due to the multi-layer complexity and slow run times. APL-UW has developed a simplified model that

duplicates two layers of GABIM physics, provides analytic partial derivatives of bottom loss and scattering with respect to seven geoacoustic parameters. An N-layer GABIM model is nearing completion. The SEPES program has implemented partial derivatives of reverberation with respect to bottom loss and scattering in CASS. We will use CASS, GABIM, and nonlinear optimization techniques to solve the bottom geoacoustic parameter estimation problem.

Appendix B

These are the general characteristics of the ITC-3013 transducer used aboard Seaglider.



Appendix C

These are the general characteristics of the hydrophones currently on the ANT Slocum.

Figure C-1. FFVS of BTech Acoustics FD series flexural disk hydrophone.

Figure C-2. Directivity patterns at 7.5 kHz for a single flexidisk hydrophone flush-mounted on bottom aft section of glider body (for bottom looking surface-noise avoiding scenarios).

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